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DREO-Developed Approach to Computer Simulation of ESD (Electrostatic Charging/Discharging) in Space Systems

L. Varga and E. Horvath

Defence R&D Canada
TECHNICAL MEMORANDUM
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DREO-DEVELOPED APPROACH TO COMPUTER SIMULATION OF ESD (ELECTROSTATIC CHARGING/DISCHARGING) IN SPACE SYSTEMS

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Abstract

Space radiation has deleterious effects on satellite electronic components and systems. To be able to predict the likely radiation scenario for a given orbit and space platform, DREO has developed a modeling tool that simulates radiation effects such as electrostatic charging/discharging (ESD) and dose deposition into complex targets. The codes used by the model are described in considerable detail. The most important code is the Monte Carlo radiation transport code for electrons and gammas. Complex targets are assembled using combinatorial geometry approach utilizing the code called "Builder", developed in-house. The results are displayed, also with in-house developed code called "Docker". Several examples of deep electrostatic charging (ESD) in dielectric materials, satellite and components are given. Manuals for the "Docker" and the "ACCEPT" codes are available upon request.

Résumé

Le rayonnement de l'espace a des effets délétères sur les composants électroniques et les systèmes satellites. Pour pouvoir prévoir le scénario probable de rayonnement pour une plateforme donnée d'orbite et d'espace, DREO a développé un outil modelant qui simule des effets de rayonnement tels que charging/discharging électrostatique (ESD) et dépôt de dose dans les cibles complexes. Les codes employés par le modèle sont décrits dans le détail considérable. Le code le plus important est le code de transport de rayonnement de Monte Carlo pour des électrons et des gammas. Des cibles complexes sont assemblées en utilisant l'approche combinatoire de la géométrie utilisant le code appelé le " constructeur ", développé intérieurement. Les résultats sont affichés, aussi avec le code développé interne appelé " Docker". Plusieurs exemples du remplissage électrostatique profond (ESD) dans les matériaux, le satellite et les composants diélectriques sont donnés. Les manuels pour des codes "Docker " et " ACCEPT " sont disponibles sur demande.

105-03221/

Executive summary

Many satellite components such as thermal blanket, solar cell windows, cable insulation, electronic boards and solid-state device packages and parts are made of dielectric materials. When exposed to the ionizing space radiation environment, these materials trap the charged corpuscular space radiation, which results in a build-up of internal electric field. Consequently, without sufficient charge dissipation, the strength of the electric field increases beyond the breakdown field of the material and discharge occurs. Consequences of uncontrolled discharge in the spacecraft vary from simple signal upsets or material damage to system burnout. Radiation also damages the semiconductor material in solid-state device; long-term exposure will alter the functionality of the device, in extreme case cause even device destruction.

DREO has developed radiation effects modeling tool that can predict with high degree of accuracy the radiation levels inside a satellite and thus calculate the amount of radiation that a particular device of other critical object will receive for a given mission. This will allow the satellite bus designer to ascertain if the critical device will be able to withstand the radiation level at the designated location inside the satellite or will have to be moved to more shielded position. This document provides information about the approach taken and codes used. First the codes are discussed, followed by several application examples to indicate to the capability of the approach.

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Sommaire

Beaucoup de composants satellites tels que la couverture thermique, les Windows de pile solaire, l'isolation de câble, les panneaux électroniques et les modules et les pièces de dispositif semi-conducteur sont faits de matériaux diélectriques. Une fois exposés à l'environnement de rayonnement de l'espace, ces matériaux emprisonnent le rayonnement corpusculaire chargé de l'espace, qui a comme conséquence un habillage de champ électrique interne. En conséquence, sans dissipation suffisante de charge, la force des augmentations de champ électrique au delà de la zone de panne du matériel et la décharge se produit. Les conséquences de la décharge non contrôlée dans le vaisseau spatial changent des renversements simples de signal ou des dommages matériels au grillage de système. Le rayonnement endommage également le matériel de semi-conducteur dans le dispositif semi-conducteur; l'exposition à long terme modifiera la fonctionnalité du dispositif, dans une destruction de dispositif de cause de cas extrême même.

DREO a développé des effets de rayonnement modelant l'outil qui peut prévoir avec le degré élevé d'exactitude les niveaux de rayonnement à l'intérieur d'un satellite et calcule ainsi la quantité de rayonnement qu'un dispositif particulier de l'autre objet critique recevra pour une mission donnée. Ceci permettra au créateur satellite de bus de vérifier si le dispositif critique pourra résister au niveau de rayonnement à l'emplacement indiqué à l'intérieur du satellite ou devra être déplacé à la position plus protégée. Ce document fournit des informations au sujet de l'approche adoptée et des codes utilisés. D'abord les codes sont discutés, suivi de plusieurs exemples d'application pour indiquer à la capacité de l'approche.

Varga L and Horvath E. 2001. DREO-DEVELOPED APPROACH TO COMPUTER SIMULATION OF ESD (ELECTROSTATIC CHARGING/DISCHARGING) IN SPACE SYSTEMS. DREO TN 2001-068 Centre de recherche pour la défense Ottawa

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1. INTRODUCTION

Numerous in-orbit anomalies in satellites have been documented (see for example NASA Reference Publication 1375) over the last two decades. Many anomalies and spurious events observed have been attributed to the accumulation of high-energy electrons in the metal and dielectric components of satellites [1]. Good correlation between the anomaly occurrence and the peak E>2MeV electron flux at geosynchronnous orbit (measured by GOES satellites) has been, in general, established [2,3]. The anomalies encountered ranged from minor telemetry glitches to more serious ones such as loss of attitude control, which in a few cases led to premature mission termination. Design procedures and guidelines published to date have provided the system design engineers with some means to alleviate these phenomena [2]. Computer codes to analyze surface charging have also been developed. For example, the NASA Charging Analyzer Program (NASCAP) has the capability of providing designers with information regarding potential distribution on the surface of the spacecraft based on the predicted radiation environment of the spacecraft orbit.

Attention has also been focused on the effect of high-energy space electrons charging the dielectrics inside spacecraft at geosynchronous orbit [3]. Because of their penetration capability, these high energy electrons will pass through the skin of a spacecraft and can become embedded inside the dielectric materials of cable harnesses, connectors, electronic circuit boards, and both active and passive electronic devices. Charge in these parts will build up if the rate of charge deposition exceeds their respective leakage rates. The charge accumulation can set up an internal electric field, which can reach the dielectric breakdown threshold field leading to an arc discharge. The electromagnetic energy released during the discharge can couple into an electronic system and cause logic upsets, phantom commands, or even circuit burnout.

Realistic deep charge deposition analysis requires utilization of a radiation transport Monte Carlo code. Computing power has grown enormously over the last three to five years so it is becoming feasible to utilize 3D Monte Carlo codes to simulate space environment-spacecraft interaction with reasonable statistical accuracy. Complex target geometry can also be realized due to ever improving computer power.

In this work, an approach to a 3D modelling of radiation effect on complex targets is described. The work was carried out to provide DREO and DND the capability to analyze electron and gamma radiation effects on electronic devices, circuit as well as complex systems.

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2. SIMULATION APPROACH AND CODES

2.1 Radiation Transport Code

Electron and gamma ray deposition into the components of the target is modelled by utilizing the electron/photon radiation transport code "**ACCEPT**". **ACCEPT** (available from Radiation Safety Information Computational Centre at Oak Ridge National Laboratory) is a 3D module of the ITS suite of electron/photon radiation transport codes suitable for application where electron/photon penetration into a relatively complex 3D multi-material structure is required for study. Among other features, the code tracks energy and charge deposition into any location of the spacecraft thereby allowing identification of possible "hot target" structures within the spacecraft. Selected target structures of the spacecraft can further be subdivided into subzones to obtain information about the charge deposition distribution. This information can be used to solve for the potential distribution within the structure.

The structure of an ITS3 ACCEPT input file consists of five main sections as shown in the example below. The first section defines all the simple objects that are used to define a scenario. These consist of elements such as a sphere, rectangular parallelogram, cylinder, or cone, among others. The element definition includes locations, directions, and dimensions where applicable. The second section defines the composition of the zones that define the problem. Each zone uses any number of elements in combinatorial logic (intersections and unions) to define a 3D region of interest. Using this method, any imaginable object can be represented. The next section defines the material composition of each of the defined zones. Normally a zone can consist of only one material (some work at DREO has extended this concept to allow multi-material objects using a new ITS3 directive called ZMAT). The last two sections contain all the simulation parameters including the radioactive source information, type, position, direction, and the source strength.

An example of the ITS input file format is shown below. It is a simple simulation of a Sodium Iodine detector irradiated by 200keV electron source.

```
* 1- DIMENSIONS OF THE SIMPLE GEOMETRICAL BODIES
GEOMETRY
* 1 The Atmosphere (25 m radius)
  SPH 0.0  0.0  0.0  2500.0

* 2 Source Encapsulation (Stainless Steel Sphere)
  SPH  -100.0  0.0  0.0  0.50

* 3 Void Containing Co60 Source
   SPH  -100.0     0.0     0.0     0 34125

* 4 Box Containing the Detector
  RPP -15  15  -15  15  -15  15
```

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```
* 5 Space Inside the Box (Air)
   RPP -12.46  12.46  -12.45  12.46  -12.46  12.46

* 7 Encapsulation of NaI Crystal
   RCC -0.15875  0.0  0.0  5.3975  0.0  0.0  2.69875

* 8 NaI Crystal
   RCC 0.00  0.0  0.0  5.08  0.0  0.0  2.54

* 9 Escape
    SPH    0.0      0.0      0.0      60.0
    END

* 2-SUBDIVISION AND ASSEMBLY OF THE SCENARIO
* 1 Air Subdivide Target Body 1
 Z1 +1 -2 -4
 * 2 Source encapsulation
 Z2 +2 -3
* Void Containing Co60 Source
 Z3  +3
* Escape
  Z4  +4 -3
END

* 3-MATERIAL CUTOFF STRETCHING - MATERIAL DESCRIPTION
* Main Body
1
* Target Body
2
* Void
0
* Escape
0

* 4-SOURCE INFORMATION
ELECTRONS
ENERGY 0.2
CUTOFFS 0.001 0.001
POSITION 15.0 15.0 70.0
DIRECTION 180.0 0.0
**********
* 5-SOURCE STRENGTH
HISTORIES 1000
BATCHES  1
```

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2.2 Docker Code

Docker is 3D graphical display software developed for the purpose of:

i) To provide an aid during the target construction by allowing visual checking of the assembly. Examination can be done at macro or microscopic levels and corrections can be made if necessary. Each material is coloured thus providing a simple but powerful visual aid.

ii) To display the results of simulation. DOCKER reads in the specified ACCEPT output file(s) and graphically displays the objects defined using a colour scheme to indicate the numeric value of the results for each body defined. Several options exist to modify the units that are being displayed. A few of the display units that have been included are: energy deposition, charge deposition, charge density, surface charge density, and dose deposition.

The Instruction and Help document for DOCKER visualization software is available from the radiation effects group at DREO.

2.3 Builder Code

As computing power for the simulation environment increases, the problems being examined become more and more complex. The setup of a problem begins to take more time than the actual simulation due to the critical step of verification of a model. The Builder code was designed to aid in the creation of complex problems and help in the verification of these models. It was designed to create models for the ITS3 TIGER Series of Monte Carlo codes, specifically for the 3D code called ACCEPT. Previous work has been conducted in simulating 3D scenarios with this code and visualizing the models and analyzing the results using the DREO code DOCKER. The code allows the designer to build up a library of basic parts that may be reused in the design. More complex components can be created from these parts and also placed in the library. This modular design allows the quick creation of a complex scenario without specifying every instance of a part manually.

All files created by Builder maintain the structure of an ACCEPT file so that the output can be directly simulated by ITS3 or visualized by DOCKER. This ability allows immediate use of a model and verification of the model, respectively. Since verification of a model is so vital to generating meaningful results in a simulation, some model checking features have been added to Builder. Any elements that are defined, but not used in a zone definition are flagged as an error. Similarly, any element that comprises the main definition of more than one zone is flagged as a warning for the designer to verify. All elements are verified to be correctly defined, such as the correct number of parameters, positive values for radii, etc.

A model, as stated earlier, is built using combinatorial geometry. This structure is maintained in Builder when library objects are added to a design. Normally, when library object number one is inserted into object number two, object number two no longer defines the 3d region of object number one. Thus, in the zone definition of object number two, the elements comprising object number one are subtracted. In specifying the addition of library object number one, the zone to subtract the 3d region from can be specified (an example is adding a desk into a room full of air, the air does not exist in the region of the desk; thus the

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zone definition of the room must subtract the 3d elements that comprise the desk). If the library insertion is not a straightforward task (such as adding a ventilation pipe that extends through several rooms), then Builder is capable of making the correct subtractions automatically. In this way, some human error can be eliminated.

The ability to add library objects into a design greatly simplifies design. First, each library object can be created and verified in small manageable phases to ensure accuracy. Secondly, objects that appear several times in a design can be quickly inserted without manually replicating the design. All that is required are the x, y, and z offsets to place the library object. Builder creates a batch script from the user input to allow re-use and modification of a particular design. This not only ensures repeatability, but also allows the designer to try various building blocks in the design for optimal performance. It also allows minute adjustment by the designer. If a number of elements or zones need to be added in at a particular location, Builder can create that space and renumber all elements and zones in the design to allow manual insertion of the desired definitions. Also, Builder can delete any specified elements or zones and renumber the remaining items. The material values remain consistent with the original intent of the design.

The final output file from Builder is a full ITS3 ACCEPT file that can be used by ITS3 or DOCKER, for simulation or verification, respectively. This output file is fully documented so that it is clear what actions have been performed to obtain this file. Builder also has the ability to mirror objects about any axis if a design requires it. It is also simple to simply swap axis to create an object that faces a different direction. The library consists of several objects and this library can be enhanced. First, any new library object is verified for correctness before being added to ensure the viability of the library. Each library object is added to the library with a user-supplied description that is added to the final design comments. As it can be determined, Builder comprises a vital tool in the process of designing a model for 3D simulation.

3. APPLICATIONS

A large variety of applications of these codes, some of which are described below, extend from simple analysis of dielectric specimen charging to spacecraft charging analysis.

3.1 Acrylic Specimen Charging

One of the earliest code applications was the simulation of a dielectric charging experiment that was conducted at the University of Toronto. The dielectric samples were 5.0 x 5.0 x 0.6 cm^3 and made of acrylic with wire probes at 0 mm, 2 mm, and 4 mm depth to enable measurement of the potential. Samples were irradiated with 1 nA 20 keV electron beam current or by a 0.1 Ci $^{90}Sr/^{90}Y$ beta source. The potential was tracked as a function of time.

In the simulated setup [2], the acrylic samples were subdivided into a 50 x 100 x 72 array of rectangular subzones to obtain information about the charge distribution within the sample. This information was subsequently used to calculate the potential distribution for comparison

with the experiment. We used $1x10^8$ histories to model the 20 keV electron beam while the $^{90}Sr/^{90}Y$ source was modelled with 3.36×10^7 histories over 8 energy windows ranging from 0 to 2.28 MeV. The 20 keV electrons penetrated only into the top layer of subzones (approx. 80 microns thick) of the acrylic sample. The $^{90}Sr/^{90}Y$ beta electrons were capable of depositing charge throughout the volume of the acrylic sample with most of the charge along the top surface as shown in Figure 1 a). Panel (b) shows the potential distribution obtained by solving Poisson's equation with the desired electron density in 3D. The calculated and experimental potentials, after extrapolation to experimental exposure time periods, are compared in Figure 2. Note the closeness of agreement for the 20 keV source while the $^{90}Sr/^{90}Y$ results differed significantly. We attribute these discrepancies to the differences in electron spectra between the simulated source and the real source. For $^{90}Sr/^{90}Y$, the source packaging alters the $^{90}Sr/^{90}Y$ emission spectrum. In our simulation we used the output from the ORIGEN-S code, which does not consider source packaging.

3.2 Spacecraft Charging Simulation

The structure of the model spacecraft is based on the structure of the experimental satellite STRV 1a [3]. The description of the spacecraft is given in detail elsewhere [4]. The spacecraft model contains several equipment housings containing populated circuit boards, cable harnesses with connectors, battery packs, and other components containing dielectrics.

Using the AE8 electron model at GEO as a source, the simulation results reveal that electrons with energy E<0.5 MeV do not play an important role in directly charging the internal components of this satellite (Figure 3). Effective shielding dependent, this energy threshold will be different for other spacecraft. A close look at the outer layers of the satellite model (not included) show that the electrons charge the solar cell and MLI layers as well as charge the components located inside the equipment housings of the spacecraft.

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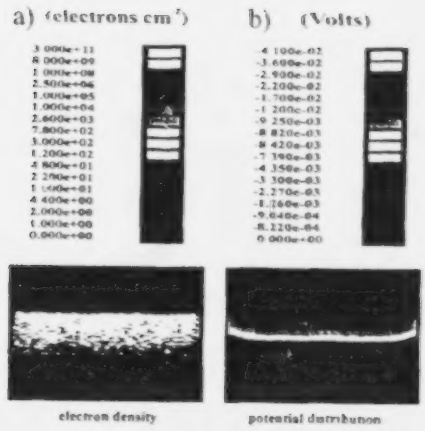

Figure 1. *Cross sectional view of the electron density distribution with most of the charge along the top surface(a) inside the acrylic specimen irradiated by a $^{90}Sr/^{90}Y$ 0.1 Ci source, and (b) showing the calculated potential distribution inside the specimen*

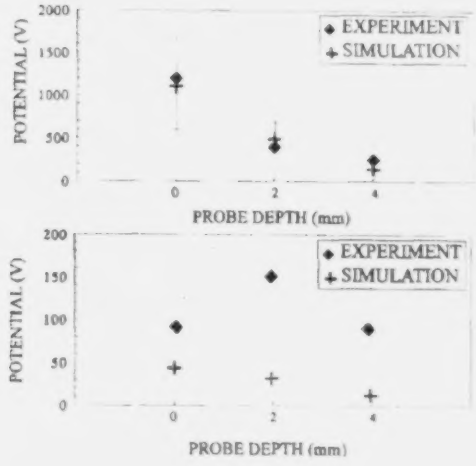

Figure 2. *Comparison of calculated and experimentally measured potential distributions inside the acrylic specimen. The top panel shows the results using a 20 keV mono-energetic electron source extrapolated to a 10 minute exposure; the bottom panel results correspond to a 0 1 Ci $^{90}Sr/^{90}Y$ source extrapolated to a 50 minute exposure.*

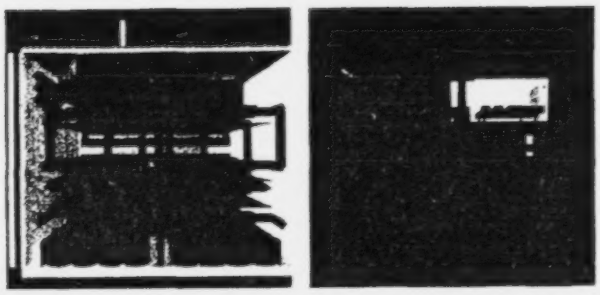

Figure 3. *Example of the electron energy effect on the internal charging rate of the model satellite. AE8 model spectrum at GEO was used in this simulation as a radiation source. The charge density scale is given in Figure 1.*

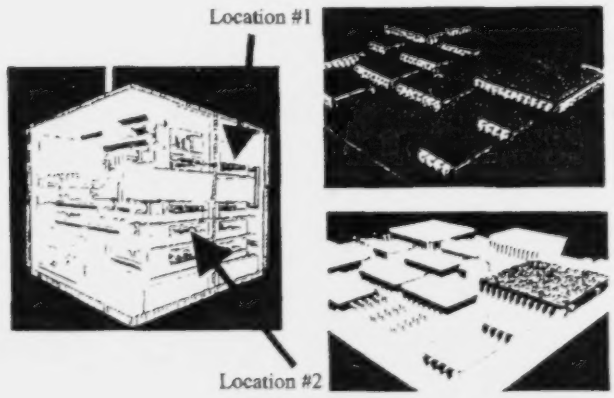

Figure 4. *Effect of location on the charging rate of an electronic board. The charge density scale is given in Figure 1.*

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The charging rates of internal dielectric components depend on their relative location. For example, under the magnetospherically disturbed conditions at GEO, we have calculated that a ceramic cover of a 48-pin solid state device would charge at the rate of 24.5 mV s^{-1} at "location #1" (Figure 4) while the same device at "location #2" would charge at a rate that is smaller by a factor of 40. In our calculations we have used a flux of 8.85 x 10^5 cm^{-2} sr^{-1} s^{-1} electrons (E>0.5 MeV) impinging on the surface of the model satellite (using GOES 8 data). It should be noted that these rates ignore the charge leakage rates and therefore represent the worst-case scenario. Figure 4 shows the charge densities for the two PCB's. One should also note the vicinity of connected metal objects, such as the ground pins and signal pins, to the ceramic top and dielectric components of PCB's. These are possible sites where a discharge can be initiated following a sudden discharge of the common ground (surface) into the surrounding plasma. Internal discharges have been observed to occur on the P78-2 satellite at times when the satellite surface was not charged [5]. This scenario can be displayed by "DOCKER", which can connect and modify charging levels on metal components.

3.3 Navigational Instrument Prototype Analysis

Spacecraft components for navigational information are often on or at the surface of a spacecraft and will be exposed to radiation and charging effects. This section examines that component of a spacecraft. Using a sectored analysis approach, the 4-pi space was divided into 5 sectors with each sector being assigned an equivalent shielding thickness of aluminium. Each of the 5 sectors was simulated with a 2-pi isotropic electron source of one million electron histories in each of eight energy bins. The results were then scaled and combined with the spectrum envelope that is characteristic for the required orbit. An example of the charging levels of the CCD imager portion of the instrument as a function of electron energy is shown in Figure 5.

4. DISCUSSION

Examples of simulating radiation deposition into complex structures have been presented to indicate how the modeling tool can be utilized. Many other applications are possible. The approach encompasses assembly software BUILDER, a 3 dimensional radiation transport Monte Carlo Code, and visualization software DOCKER. In addition, a 3 dimensional Poisson equation solver is used to calculate potential distributions inside dielectric specimens.

The simulation results of potentials compared well with the experimental values such as in the case of the mono-energetic electron beam where the spectrum of the radiation source was known. In the case involving the $^{90}Sr/^{90}Y$, the discrepancies are believed to be caused by source spectrum differences between simulated and actual electron spectra due to packaging of the source. The following discussion points out that when a source with a continuous

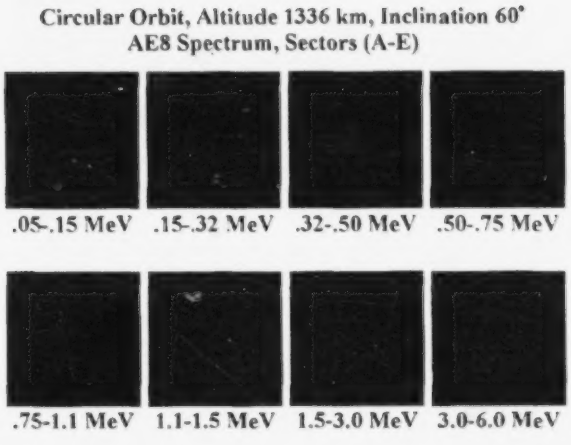

***Figure 5**. Electron energy effect on charging levels of the imaging component of the instrument. The charge density scale is given in Figure 1.*

spectrum, such as $^{90}Sr/^{90}Y$ or space electron plasma impinging on a dielectric, the whole volume of a dielectric will be subject to charging. The internal electric fields will be small when compared to a case where there is charge aggregation such as in the case of a monoenergetic beam. This was observed in the simulation of the dielectric specimen charging experiment (Figure 2) and in the charging of the STRV model satellite dielectric component. In the latter case, a charging analysis of a ceramic cover of a 48-pin solid-state device was carried out. Although the internal electric field was calculated to be small, the ceramic top as a whole over a twelve-hour period at GEO during a magnetospheric storm could reach a potential over one kilovolt. The model also revealed where a discharge can be initiated at sites where highly charged dielectric components are located close to conducting elements such as pins of solid state devices, PCB connectors or cable harnesses. At these sites, a discharge can be initiated after a sudden shift of the common ground. As this happens, the pins of the solid-state devices, cores of the cable harnesses, and ground and signal planes inside the PCB's will suddenly be at a significantly different potential than their neighbouring dielectric components. Electric fields between the charged dielectrics and interconnected metal objects become the sites for discharge initiation.

At present, as pointed out earlier, the charge leakage rate from the dielectric materials was assumed to be negligible in comparison to charge deposition rates, which, under the most charging conditions is a reasonable assumption. Work is being conducted to introduce into the simulation model the effects of photoelectric currents and dielectric charge mobility. The simulation package, being capable of pointing out the sites inside spacecraft where discharge initiation can occur, can be considered as a valuable complementary tool to other spacecraft charging codes.

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Abstract

Space radiation has deleterious effects on satellite electronic components and systems. To be able to predict the likely radiation scenario for a given orbit and space platform, DREO has developed a modeling tool that simulates radiation effects such as electrostatic charging/discharging (ESD) and dose deposition into complex targets. The codes used by the model are described in considerable detail. The most important code is the Monte Carlo radiation transport code for electrons and gammas. Complex targets are assembled using combinatorial geometry approach utilizing the code called "Builder", developed in-house. The results are displayed, also with in-house developed code called "Docker". Several examples of deep electrostatic charging (ESD) in dielectric materials, satellite and components are given.

Résumé

Le rayonnement de l'espace a des effets délétères sur les composants électroniques et les systèmes satellites. Pour pouvoir prévoir le scénario probable de rayonnement pour une plateforme donnée d'orbite et d'espace, DREO a développé un outil modelant qui simule des effets de rayonnement tels que charging/discharging électrostatique (ESD) et dépôt de dose dans les cibles complexes. Les codes employés par le modèle sont décrits dans le détail considérable. Le code le plus important est le code de transport de rayonnement de Monte Carlo pour des électrons et des gammas. Des cibles complexes sont assemblées en utilisant l'approche combinatoire de la géométrie utilisant le code appelé le " constructeur ", développé intérieurement. Les résultats sont affichés, aussi avec le code développé interne appelé " Docker". Plusieurs exemples du remplissage électrostatique profond (ESD) dans les matériaux, le satellite et les composants diélectriques sont donnés.

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Space radiation Environment, Trapped Electrons, Electrostatic Charging, Dielectrics, Charge Distribution, Monte Carlo Code, Potential Distribution

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